Hawaiian Calderas[1]

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ABSTRACT: Hawaiian calderas form by collapse during the last stages of growth of shield volcanoes built by frequent eruptions of tholeiitic basalt. They range from 2–12 miles across, have sunk several thousand feet, and in part have grown piecemeal by coalescence of smaller collapse craters. They may never have formed on some volcanoes, and all are partly or wholly filled by continued eruption. Toward the end of the filling activity slows, and alkalic lavas complete the filling and build a thin cap over the caldera.

Gravity studies reveal masses of ultra-dense rocks only 1–2 km below the surface of several of the volcanoes—perhaps olivine-rich cumulates in the feeding pipe of the volcano, or perhaps protrusions of the mantle. The idea that these may have led to formation of the calderas by isostatic sinking of a heavy column culminating in the caldera appears to be negated by the facts that some calderas show no associated gravity high, in some the high is offset to one side of the caldera, and some highs are not associated with any apparent caldera collapse.

Caldera formation probably depends on the formation of a magma reservoir within the mass of the shield volcano, with its top within a few kilometers of the summit of the shield. The Glen Coe mechanism of caldera formation seems to be ruled out by the lack of upward displacement of magma around the sinking block. Caldera collapse is probably the result of sinking of a block bounded by inward-dipping conical fractures, permitted by distension of the top of the volcano and removal of support due to drainage of magma into the rift zones, with or without flank eruption. The distension of both the summit region and the rift zones may result from a lateral spreading of the lower part of the ultra-dense core of the volcano.

THE ORIGIN OF HAWAIIAN CALDERAS has been discussed several times before (Stearns and Clark, 1930; Stearns and Macdonald, 1946; Macdonald, 1956), but with the increase in knowledge of the physical properties of Hawaiian rocks and magmas and the geophysics of Hawaiian volcanoes during the last decade it is desirable to review the former conclusions, to see whether they need modification. It may be assumed as a starting point that the calderas are formed by collapse. They obviously are not formed by erosion, and the very small amount of pyroclastic debris at and near the summits of the shields clearly eliminates any possibility of their having been blasted out by explosion. There is general agreement that they have been formed by the sinking in of the summit regions of the shield volcanoes. The term "volcanic sink" used for them by R. A. Daly (1914: 144–147) is an appropriate one, though it has not been widely used, at least partly because of potential confusion with other types of geologic "sinks."

Though the generality of the collapse origin of Hawaiian calderas is unquestioned, the cause of the sinking is still uncertain. The purpose of this paper is to describe briefly the calderas, to sketch their spatial and time relationships to the volcanic structures and history, to reexamine the suggested causes of collapse, and to suggest a new mechanism that may be of importance in bringing about the distension of the mountain that is indicated both by the sinking of the caldera and by the rift zones.

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MORPHOLOGY OF THE CALDERAS

The summits of the active shield volcanoes, Kilauea and Mauna Loa, are indented by oval calderas. That of Kilauea is 4.4 km long and 3 km wide. Mokuaweoweo caldera, at the summit of Mauna Loa, is 4.5 km long and 2.6 km wide. Both are slightly excentric with respect to the precise summits of the mountains. Kilauea caldera is 150 m deep at its western edge, beneath the highest point of the mountain, but its walls decrease in height essentially to zero at its south side. It is separated from the adjacent pit crater of Kilauea Iki by only a low, narrow ridge (the Byron Ledge). Mokuaweoweo is 180 m deep at its western edge, 130 m deep at its eastern edge. At the south it merges with the pit crater, South Pit, and at the north its floor is continuous into the pit crater known as North Bay, which is bounded at the north by a wall only about 5 m high. At its northeast edge Mokuaweoweo also merges with the very small pit crater, East Bay; and farther north the pit crater Lua Poholu lies within the outermost faults of the caldera. It is generally agreed that the pit craters, like the calderas, have formed by collapse.

Extending outward from the calderas are the rift zones of the volcanoes (zones of fracturing averaging about 3 km wide) that have served as the feeding conduits for most flank eruptions of the volcanoes. On the southwest rift zone of Mauna Loa, within 3 km of Mokuaweoweo, lie three pit craters, the central one of which has been formed since 1840. Along the east rift zone of Kilauea within 20 km of the caldera lies a whole series of pit craters (Stearns and Macdonald, 1946: Pl. 1).

In most places the boundaries of the calderas are steep cliffs, with an average slope of about 75°. Layers of lava in the cliffs slope outward away from the summit of the mountain and their truncated edges project upward into space in the present area of the depression. The vents that fed them must have been located at a higher level, and must have dropped out of sight at the time of origin of the caldera. In other words, the caldera cannot have been present in anything approaching its present dimensions until the shield had reached essentially its present size. The cliffs bounding the calderas are fault scarps. Along most of the boundary the cliff is simple, but in places it consists of a series of step-fault blocks. The fault planes separating the step blocks appear to dip toward the center of the caldera at about the same angle as the rest of the boundary scarp. Locally, the faults pass into monoclines (Macdonald, 1957).

The main calderas are partly surrounded by benches as much as 3 km wide that have also been dropped down on faults, but not as far as the central caldera. Viewed from an airplane a short distance away, the summit areas of both Kilauea and Mauna Loa are seen to have sagged downward over a subcircular area 6–8 km across, with the sharply defined downfaulted calderas at the center.

The floor of Kilauea caldera is a very gently sloping dome or cone rising to an apex at Halemaumau crater, in the southwestern part of the caldera. The cone was formed by repeated overflows from Halemaumau during the long period of lava lake activity before 1924, with the minor addition of the lava flow of the 1954 eruption (Macdonald and Eaton, 1957). The floor of Mokuaweoweo also slopes upward toward the cones of the 1940 and 1949 eruptions. During the last 150 years the history of the calderas has been one of repeated collapse of the floor and refilling by eruptions on the floors. In 1825 the center of Kilauea caldera was a pit some 260 m deep, surrounded by a narrow "black ledge" 30 m or so below the present floor level. This central depression is presumed to have formed by collapse at the time of the flank eruption in 1823. By 1832 the central pit had been filled to overflowing, but in that year it was reestablished in much its former condition by another collapse. Again it was refilled, only to be reformed by collapse accompanying the eruption of 1840. Still again it was refilled, only to sag down in a less extensive depression at the time of the 1868 eruptions, and so on. From 1840 onward each collapse was smaller than the one that preceded it, until in the 1920's two small collapses were followed by a large one (Table 1). It should be noted here that the collapses of the 19th century listed in the table represent the volume

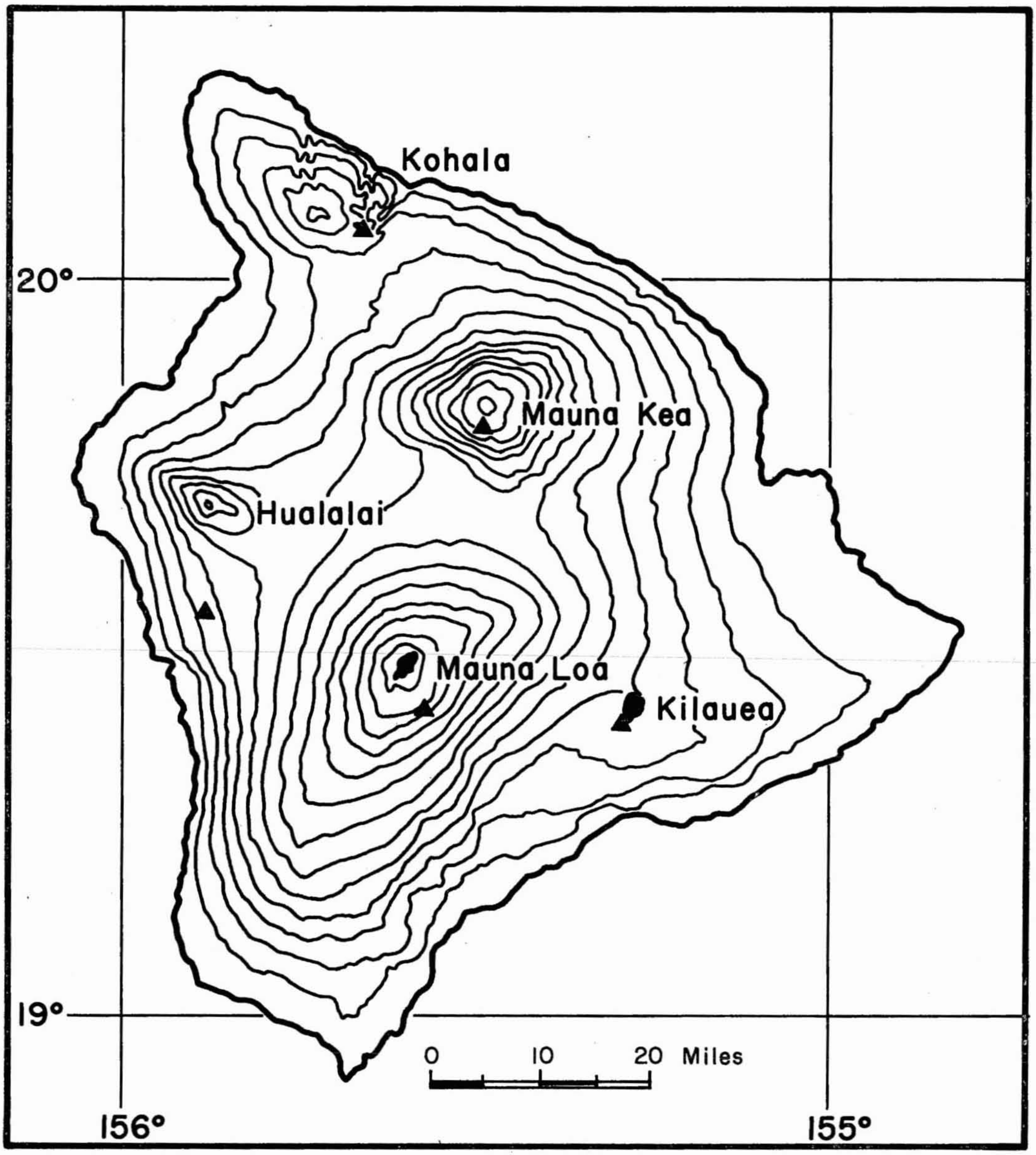

FIG. 1. Map of the island of Hawaii, showing the locations of the major volcanoes, the calderas (*solid black spots*), and the approximate centers of the gravity highs (*black triangles*) as located by Kinoshita et al. (1963).

of the sharply defined central depression only, whereas those of 1924 and 1955 include the volume of a gentle sinking of the mountaintop that could not have been detected without sensitive tiltmeters or precise surveying, so that actually the early collapses must have been somewhat larger in relation to the later ones than is indicated by the table.

The history of Mokuaweoweo is known in far less detail. A large collapse of the caldera floor in the middle part of the 19th century may have been associated with one, or possibly more than one, of the flank eruptions of Mauna Loa. Since then the depression has been gradually refilled, until in 1949 lava poured out of the caldera into South Pit, filled it to overflowing, and continued for several kilometers down the mountainside. Until 1948 a crescentic bench (the South Lunate Platform) remained around the south side of the central pit, but it has been largely buried by the lavas and cones of the 1949 eruption.

The original morphological forms of the calderas of the older Hawaiian volcanoes have been wholly destroyed by erosion, but the calderas are nevertheless clearly delineated by mapping. The lavas that filled the calderas are thick-bedded, generally moderately to very dense, and essentially horizontal, in contrast to the thin-bedded moderately to highly vesicular flows that accumulated with slopes of 2–10° on the flanks of the volcano outside the caldera. The thickness and horizontality of the caldera-filling flows resulted from their being confined within the caldera depression, and their denseness resulted from the greater proportion of gas that was able to bubble out of the thicker flows before they solidified. The contrast in general aspect and attitude of the two groups of flows is usually sufficient to indicate the former position of the edge of the caldera. In addition, banks of talus commonly formed against the foot of the caldera-boundary cliffs, as they are doing in Kilauea and Mauna Loa calderas today. The lavas accumulating within the caldera buried these taluses, and later erosion has exposed them as prisms of breccia between the caldera-filling and extra-caldera lavas. Careful mapping by H. T. Stearns has delineated the calderas of the Koolau and Waianae volcanoes on Oahu, and those on east Molokai, West Maui, and the exposed end of that of Kahoolawe. The caldera of the Koolau volcano was about 8 km long and 5 km wide, cen-

TABLE 1

VOLUMES OF CALDERA COLLAPSE COMPARED WITH VOLUMES OF FLANK LAVA FLOWS AT KILAUEA VOLCANO DURING HISTORICAL TIMES

YEAR	VOLUME OF COLLAPSE (m^3)	VOLUME OF FLANK LAVA FLOWS (m^3): Actual	VOLUME OF FLANK LAVA FLOWS (m^3): Reduced to approximate volume in magma chamber
1823	539,500,000	14,000,000[a]	11,200,000
1932	580,600,000	?	....
1840	219,500,000	214,800,000[b]	171,800,000
1868	188,300,000	<5,000,000	<4,000,000
1886	39,600,000	?	....
1891	34,000,000	?	....
1894	8,500,000	?	....
1916	8,300,000	0	0
1919	10,000,000	73,800,000[c]	59,000,000[c]
1922	21,200,000	8,700,000[d]	7,000,000
1924	201,600,000	0	0
1950		0	0
1955	200,000,000	141,000,000	113,000,000

[a] Includes an estimated 2,000,000 m^3 that poured into the ocean.
[b] Includes an estimated 150,000,000 m^3 that flowed into the ocean.
[c] Includes the volume of the flow in the caldera in 1919 and the flow on the southwest rift zone in 1919 and 1920.
[d] Includes the volumes of flows on the caldera floor in 1921 and on the east rift zone in 1922.

tering at the Kawainui Swamp near Kailua (Stearns, 1939: Pl. 1). That of east Molokai was about 7.2 km long and 5 km wide (Stearns, and Macdonald, 1947:19, Pl. 1). The largest of the Hawaiian calderas was that of Kauai, some 16 by 20 km across (Stearns, 1946: Fig. 22; Macdonald, Davis, and Cox, 1960: Pl. 1). In and close to the east Molokai and Koolau calderas, and locally in that of West Maui and near the boundary of that of Kauai, rising gases brought about chloritization of the rocks and deposited secondary minerals, including quartz and chalcedony. The boundary cliffs of the calderas, as delineated by mapping, sloped inward at angles of 50° to nearly 90°, averaging about 75°. The slope of the boundary cliffs is not, of course, necessarily the same as that of the faults that bound the sunken block at depth. Outward-dipping faults would produce surficial scarps that are unstable, and slumping would quickly form inward-sloping fault-line scarps. However, other evidence discussed on a later page also suggests that the subsurface faults dip inward.

Nowhere has the bottom of the caldera-filling mass been reached by erosion. The sinking of the original tops of the east Molokai and Kauai shields exceeded 1,400 m.

There is considerable evidence that Mokuaweoweo caldera grew in part by the repeated inclusion of marginal pit craters (Stearns and Clark, 1930:49; Stearns and Macdonald, 1946: 29). On the floor of Kilauea caldera also, the distribution of areas of alteration of the rocks by rising gases indicates the presence of a series of pits buried by the lavas erupted within the last 150 years (Macdonald, 1955*a*). The Kilauea Iki and Keanakakoi pit craters nearly coalesce with the inner caldera of Kilauea, and the outermost caldera faults are beyond them, so that they are actually within the major sunken area. The pit craters probably have formed by sinking of a roof block into an underlying magma chamber eaten upward into the mass of the volcano by stoping and melting of the lavas above the magma body (Macdonald, 1956:281), but since the sinking is not accompanied by a rise of magma along the bounding ring fractures into the crater the magma must have been withdrawn, into adjacent rift fractures or elsewhere, to make room for the sinking block.

RELATION OF CALDERA FORMATION TO VOLCANIC AND MAGMATIC HISTORY

As a result of his years of study of the areal geology of the Hawaiian Islands, H. T. Stearns was able to distinguish a series of stages in the history of the volcanoes (Stearns, 1940; 1946: 17–19). These may be summarized briefly as follows, with some additions and modifications from Stearns' original statements:

1. A youthful shield-building stage, during which frequent eruptions of very fluid basaltic lava build a shield volcano composed almost wholly of thin extensive lava flows. Eruptions come so frequently that there is not time for any appreciable amount of weathering or erosion between successive flows. Pyroclastic material forms probably less than 1% of the part of the shield above sea level. Hydromagmatic explosions may have produced a much larger proportion of pyroclastics in the zone within a few hundred feet below sea level, but at greater depths the pressure of overlying water probably effectively restrained both explosion and vesiculation, and the lava flows were probably much denser than those later poured out above sea level, as are those formed in deep water on the east rift zone of Kilauea (Moore, 1965).

2. Late in the period of shield building the summit of the shield collapsed to form the caldera. There followed the so-called caldera-filling period, during which thick massive lava flows accumulated within the caldera, gradually filling it. It should be noted, however, that eruption is not restricted to the caldera, but continues to take place on the flanks of the volcano also, and the shield continues to build. Volcanism continues vigorous and eruptions frequent; the activity remains almost purely effusive and pyroclastic material still is formed in only very small amount.

3. Eventually the caldera becomes filled and the volcano enters on the post-caldera, or old-age, stage. Eruptions become less frequent, and many of them are more explosive, partly because of greater viscosity of the erupting magma but partly also because of a greater abundance

of gas. Local erosional unconformities, stream gravels, and soil beds are found between successive flows, and the proportion of pyroclastic material increases. The spatter cones built by Hawaiian-type eruptions characteristic of the shield-building stage are largely replaced by cinder cones built by strombolian-type eruptions. A relatively thin cap, a few tens to several hundreds of meters thick, is built over the top of the shield and the filled caldera.

4. Extinction of the major volcano is followed by a long period of volcanic quiescence, with deep erosion and weathering. Sea cliffs several hundred meters high and canyons several hundred meters deep are cut into the volcanic mountain.

5. At some volcanoes (whether eventually at all is unknown) volcanic activity returns. In this rejuvenated, or post-erosional, stage new eruptions take place from rift zones that have little or no relationship in position or direction to those of the earlier stages. Lava flows partly fill valleys and relatively small lava, cinder, and tuff cones are built against the dissected surface of the old mountain, separated from it by a profound erosional unconformity and sometimes by intervening sedimentary deposits such as coral reefs.

It should be noted that not all Hawaiian volcanoes have passed through all of the above stages. Lanai appears to have stopped activity at about the end of the caldera-filling stage. Kilauea and Mauna Loa are still in the caldera-filling stage and Hualalai appears to have barely entered the old-age stage. Neither Hualalai nor west Molokai now has any caldera, nor do they show any indication of ever having had one, though on both a caldera may have been hidden by later flows. On Mauna Kea the suggestion of a former caldera is very tenuous, consisting only in an arcuate arrangement of some of the cinder cones in the summit region that may reflect caldera-related ring fractures at depth (Macdonald, 1945). These volcanoes may have skipped the caldera-forming and caldera-filling stage.

Recent petrographic studies (Macdonald and Katsura, 1964) have demonstrated the relationship of rock types to the eruptive history outlined above. The lavas of the shield-building and most of the caldera-filling stages are tholeiitic basalt (including tholeiite, olivine tholeiite, and oceanite). In the upper part of the caldera-filling sequence, and at a corresponding stratigraphic level outside the caldera, there occurs a change to alkalic lavas (alkalic basalt, olivine basalt, ankaramite, hawaiite, mugearite, and trachyte), and these rock types persist through the old-age stage. The rocks of the post-erosional stage are characteristically nephelinites and melilite-nephelinites, with associated undersaturated alkalic olivine basalts.

Thus the formation of the calderas, though it may vary somewhat from one volcano to another and may be lacking from some, takes place during the end of the period of shield building, while volcanism is still vigorous, and somewhat before the slowing down of volcanism that accompanies the change of petrographic types from tholeiitic to alkalic.

One important bit of evidence that should be considered in relation to the origin of the Hawaiian calderas is that the caldera floor sometimes moves upward as well as downward. Not only does the floor swell up as a broad flat dome during tumescence of the volcano (Jaggar and Finch, 1929), but it may move en masse in the manner of a huge piston. The great collapse of Kilauea caldera in 1840 produced a central pit 1.5 km wide, 3 km long, and about 150 m deep. About 1845 the floor of the pit started to rise bodily, and by 1850 it had risen about 150 m and was approximately level with the "black ledge" that surrounded it. The taluses that had accumulated on it at the foot of the bounding cliffs had been pushed up until they stood as arcuate ridges of angular rock fragments that projected as much as 45 m above the surrounding caldera floor. Although it is possible that this elevation of the caldera floor could have resulted from shallow intrusion of magma beneath it, as did the elevation of the floor of Halemaumau crater in 1952 (Macdonald, 1955*a*), it appears more probable that it was caused by inflation of the underlying main magma chamber of the volcano.

INTERNAL STRUCTURE OF THE VOLCANOES

In none of the Hawaiian volcanoes has erosion cut deeply enough to expose the congealed magma body that fed the surface eruptions. Knowledge of the position and nature of the magma chamber is almost wholly implied from seismic evidence and the pattern of swelling and shrinking of the volcano before and after eruptions. Earthquakes originating from a depth of about 60 km below sea level, within the upper part of the earth's mantle, are accompanied by "harmonic" tremor that appears to be the same as the tremor that is known to accompany movement of magma in the volcanic conduits close to the surface. From this it is implied that the magma that feeds the volcano is formed at a depth of about 60 km (Eaton and Murata, 1960). It has long been known that Kilauea volcano gradually tumesces over periods ranging from a few weeks to several years before eruptions (Jaggar and Finch, 1929), presumably because of inflation of an underlying magma reservoir, and detumesces during and after the release of magma by eruption. Recent analyses of the patterns of ground tilting resulting from the tumescence and detumescence, coupled with the depth distribution of the shallow-seated earthquakes that precede eruptions, have led to the conclusion that the top of the magma body lies at a depth of only about 2 km below the summit of Kilauea volcano (Eaton and Murata, 1960). It should be emphasized that this is well above the level of the surrounding ocean floor and consequently well within the mass of the volcanic mountain itself. Room for the magma body must have been obtained either by lateral displacement of its margins or by melting of the rocks that formerly constituted the core of the volcano.

The lateral extent of the magma body is less certain, and indeed it appears doubtful (from inductive reasoning) that it has any sharply defined margin. More likely there is a gradual passage from freely fluid magma to somewhat plastic but essentially solid material, and thence to the truly solid rocks of the volcano's exterior. There can be no question that the magmatic core, or at least material in a very mobile condition, extends outward from beneath the summit of the mountain for many kilometers into the rift zones. Thus, the 1955 eruption of Kilauea from the east rift zone 30 km east of the caldera was preceded by a marked swelling of the rift zone, with lifting of the ground surface along the crest of the rift-zone arch in the eruption area of more than a foot (Macdonald and Eaton, 1964:105).

There is no real evidence of magma chambers at shallow depths beneath the other Hawaiian volcanoes. Even at Mauna Loa the measurements of tilting are far from sufficient to demonstrate such a chamber. By analogy with Kilauea, however, it may be assumed that such magma chambers probably exist, or did exist when the volcano was active. The collapse of the shield to form the caldera is probably dependent on the existence of this magma body, and the fact that caldera formation does not occur until near the end of the shield-building stage is probably because sufficient remelting of the core of the shield to form the chamber has not taken place until that stage.

During recent years gravity studies in the Hawaiian Islands have indicated very high values in and near the areas of some of the calderas (Woollard, 1951; Woollard et al., 1964). Strange, Woollard, and Rose (p. 381 in this issue) reports that whereas the average Bouguer gravity anomaly value along the Hawaiian ridge is about +200 mgal, the intensity in the central parts of the Koolau and Waianae calderas, Oahu, is in excess of 310 mgal, and "the maximum Bouguer anomaly values over most of the volcanic centers range between +285 and +325 mgal." He points out, as had Woollard (1951), that to explain the anomalies it is necessary to assume a very high density for the material in the volcanic "pipes." Similarly, Adams and Furumoto (p. 296 in this issue) and Furumoto, Thompson, and Woollard (p. 306 in this issue) find seismic velocities in the Koolau "plug" greater than 7 km/sec, as compared with 4.6 km/sec in surrounding material. Adams estimates the plug to be about 6 km across, with its top about 1.6 km below sea level. Similar high seismic velocities were found by Shor (1960) approaching close to the surface in the northwestern part of the Hawaiian ridge, near the Gardner Pinnacles. To explain the observed pattern of high gravity values combined with high seismic velocities, one is forced to assume rocks beneath the Oahu calderas with densities approximating 3.2 gm/cc extending to at least the depth of the ocean floor (5.5 km). Very dense caldera-filling tholeiitic basalts may have densities up to a little more than 3, and oceanites have measured densities ranging up to about 3.2; but of Hawaiian rocks only the peridotites found as inclusions in flows have consistently a density greater than 3.2.

The dense high-velocity rock has generally been considered to be part of the earth's mantle injected to high levels in the crust. However, it conceivably could be cumulate material settled from the overlying magma in the conduit and core of the volcano or lagging behind as the more fluid portion of the magma rose around it. Fragments of dunite and wehrlite brought up by lavas of the old-age stage of the volcanoes, such as the 1801 eruption of Hualalai (Macdonald, 1949:76; Richter and Murata, 1961) have textures resembling those of the cumulate rocks of layered intrusives (Wager, Brown, and Wadsworth, 1960) and probably represent fragments of cumulate rock brought up from relatively shallow depths beneath the volcano. The mineral assemblages are not particularly indicative of high-pressure equilibria. On the other hand, the garnet pyroxenite ("eclogite") found as inclusions at Salt Lake Crater on Oahu does represent a high-pressure equilibrium assemblage, and quite probably represents material brought up from the mantle. In chemical composition it is very close to tholeiitic oceanite, though somewhat richer in silica and poorer in alkalies (Macdonald and Katsura, 1964: Table 8, col. 13), and may represent an oceanitic intrusive mass crystallized under high pressure in the upper mantle. Its density (2.71–2.81) and seismic velocity ($V_p = 5.52–6.06$) as determined by Manghnani and Woollard (p. 291 in this issue) are too low to account for the material in the primary volcanic "pipes," which is characterized by high gravity values. Moreover, there is no significant gravity "high" associated with Salt Lake Crater.

Brief mention of the rift zones of Hawaiian shield volcanoes has already been made. The rift zones generally radiate outward from the summit of the shield—that is, from the caldera. Usually there are three distinct rift zones, with angles of roughly 120° between them, and with one rift zone less well developed than the others. In addition to the lines of spatter cones and cinder cones resulting from eruption, the rift zones are marked by pit craters, many open fissures, and by long narrow grabens. The depth of the grabens is generally unknown, because they have been partly filled with later lava. At depth in the older, dissected volcanoes, the rift zones are marked by thousands of thin dikes. Sections across them yield counts of more than 600 dikes per mile. Although a few instances of strike-slip displacement on rift-zone fissures are known (Macdonald, 1956:278), the configuration of the walls of the dikes generally indicates horizontal opening without any appreciable displacement parallel to the fissure. There can be no question that the rift zones represent a very considerable distension of the visible part of the shield volcano, a distension on the order of 0.75–1 km.

The Hawaiian rift zones have recently been explained by J. G. Moore (at a lecture before the Peninsula Geological Society, Stanford University, January 7, 1965) as the result of landsliding on a gigantic scale. Specifically, he believes that the southern slope of Kilauea is sliding seaward, the fractures on which the movement is taking place steepening to near verticality to form the east rift zone, with graben collapse along the upper edge of the sliding block. The distension in the rift zone he attributes to the southward movement of the block to the south. He supposes that magma makes its way surfaceward along the plane of sliding. Essentially the same suggestion was made for the origin of the southwest rift zone of Kilauea by Stearns and Clark (1930). Without at present entering into any debate on whether or not there is large-scale landsliding going on along the south flank of Kilauea, it appears very unlikely to me that the east rift zone (or any other) can have the origin suggested by Moore. The essentially vertical attitude of the dikes in the rift zones down to the deepest level of exposure on the deeply eroded islands of Oahu and Kauai, a level equal to more than half of the probable depth to the magma chamber at Kilauea, is inconsistent with such an origin. So also is the fact that the gravity highs that extend laterally as bulges from the highs beneath the calderas usually coincide closely with the surface trace of the rift zones (Kinoshita et al., 1963: Fig. 1; Strange et al., Fig. 1, p. 382 in this issue). Whether the high value of gravity over the rift zones is due to exceptionally dense material at depth or whether it is wholly the result of a large number of dense dikes, if the path of the rising magma were inclined markedly to one side at shallow depth the gravity high should not only lie to one side of the rift zone, but should be only a fraction of the magnitude observed and of much greater width. The close coincidence of the "high" and the surface rift zone, therefore, strongly suggests continuation of the rift zone essentially vertically at depth. Furthermore, before any landslide or landslide-induced rift could exist, there must have been a volcanic mass for the slide to form upon. The east rift zone of Kilauea occupies the top of a gentle constructional arch that extends all the way to the sea floor, more than 100 km east of the summit of the shield. The arch has obviously been built by eruptions from the rift, and the shape of the shield is fundamentally governed by the position of the rift zone. The same is true of the other Hawaiian shields. The shields are generally not round or oval, but lobate, resembling three-pointed stars in ground plan (Wentworth and Macdonald, 1953), as a result of building by eruptions predominantly along the three rift zones. The close dependence in shape of the major shields upon the position of the rift zones indicates that the rifts are earlier-formed and are more fundamental structures than any produced by landsliding.

Displacement of the ground surface during the 1955 eruption on the east rift zone of Kilauea (Macdonald and Eaton, 1964) involved slight elevation of the surface adjacent to the eruptive fissures, sinking of a graben along the rift, and lateral displacement of the ground outside the graben by an amount up to a little more than 1.5 m in a direction essentially normal to the rift. There was no detectable sinking of the surface outside the graben on either side of the rift in relation to the other side.

The predominance of earthquake foci south of the rift zone noted by Moore is probably related to movement on faults of the Hilina system, which lies along the south slope of Kilauea and converges eastward with the rift zone (Stearns and Macdonald, 1946: Pl. 1), rather than to movement on the rift zone itself. Commonly, groups of earthquakes on the rift zone are quite distinct from those originating farther south, as is clearly shown on the map published by Koyanagi (1964).

The rift zone pattern is closely similar to that resulting from distension of the surface of domes pushed up over intrusions (Cloos, 1955); and the most probable cause of Hawaiian rift zones still appears to be inflation of the volcano by intrusion of magma within it.

CAUSES OF CALDERA COLLAPSE

Two principal hypotheses have been advanced to account for the sinking of the summits of the Hawaiian shields to form calderas. Both depend upon the presence of a magma body of at least moderate size at a shallow depth beneath the summit area—a once-hypothetical magma body the actual existence of which now appears to be demonstrated. Williams (1941: 246, 286–292) took the Hawaiian calderas as examples of his calderas of "Kilauean type," which he believed resulted from removal of support caused by drainage of magma from beneath them, caused in turn by rapid effusion on the flanks of the volcano or intrusion as dikes or sills. Stearns and Macdonald (1946:33) suggested as an alternative explanation that the calderas resulted from weakening of the summit area by large-scale magmatic stoping and cauldron subsidence as in the Scottish ring complexes—calderas classified by Williams (1941: 246) as the "Glen Coe type." The mechanism of their formation was believed to be the upward enlargement of the magma body by stoping and cauldron subsidence until the overlying crust became too thin and weak to support itself, when ring fractures developed and the surficial block sank into the underlying magma because of its greater density. The same mechanism should operate if the enlargement of the underlying magma chamber was largely by melting of the enclosing rocks instead of by stoping.

Reynolds' (1956) suggestion that the Scottish cauldron subsidences and the calderas that presumably lay above them were formed by the gas-coring mechanism suggested by Escher (1929), with "fluidization," intrusion, and ejection of an ignimbritic solid-gas emulsion, can have no bearing on Hawaiian calderas because of the complete absence in Hawaii of ignimbritic material and the extreme paucity of fragmental explosive material of any sort.

Before considering further these older hypotheses, let us look briefly at a new one. The very high density of the material in pipe-like masses beneath the summit areas of Hawaiian volcanoes has led to the suggestion that the formation of a caldera might be the result of the isostatic sinking of the heavy column, carrying the overlying mountain top down with it. In this connection it is necessary to consider the gravity field found by Kinoshita and others (1963) on the island of Hawaii. Their Figure 1 shows that the gravity high for Mauna Loa (a Bouguer anomaly reaching between 330 and 340 mgal) is offset several kilometers to the southeast of Mokuaweoweo caldera, farther to one side than is the presumed top of the dense material below the surface. There is no sign whatever of sinking of the mountain surface above the center of the gravity high. The high for Kilauea (reaching about 315 mgal) also is excentric to the caldera, the center of the high lying some 2 km or more to the southwest of the center of the caldera. Thus, it appears unlikely that the caldera formation can have resulted simply from isostatic sinking, unless the improbable mechanism of a highly oblique subsidence is invoked. Furthermore, no discernible sinking has disrupted the post-caldera cap on volcanoes such as Mauna Kea, beneath which a markedly high gravity anomaly still exists (Kinoshita et al., 1963). Isostatic sinking in the ordinary sense, therefore, appears improbable as an explanation for the Hawaiian calderas.

The high-density column beneath the volcanoes may have another effect, however. Rising, as it apparently does, some 5 km or more above the base of the volcanic mountain, the base of the mass must have a considerable tendency to spread, and must exert a considerable lateral thrust on the lighter material adjacent to it. This must be particularly true when the mass is still somewhat mushy. Does the tendency for the heavy mass to spread result in spasmodic lateral movements of its lower part into the proximal ends of the rift zones, causing a wedging open of the rift zone and a distension of the volcanic edifice?

The principal reason given by Stearns and Macdonald (1946:29–33) for the rejection of Williams' proposed mechanism for formation of calderas of Kilauean type was the fact that flank eruptions with voluminous drainage of magma are frequent throughout the period of building of the shield, whereas the formation of the caldera takes place only near the end of it. Actually, however, if the formation of the caldera depends on the existence of a magma chamber in the core of the volcano, the absence of such a chamber in the earlier stages would account for the absence of a caldera. Considerable time must be necessary for enlargement of the chamber to the point where its roof is too broad and thin to support itself.

A more conclusive argument can be made against the application of the Glen Coe mechanism to Hawaiian calderas: namely, the fact that the sinking caldera block must displace an equal volume of magma. Where does this magma go? Does it rise into the ring fractures around the sinking block, as in the classical interpretation of the cauldron subsidence of Glen Coe (Clough, Maufe, and Bailey, 1909: Fig. 14)? There is no evidence to suggest it. Dikes are nearly absent along the caldera boundaries at levels exposed by erosion. Eruptive vents on the caldera-boundary fractures are very rare, and the few that are found appear to have no fundamental relationship to the fracture. Thus, although the main cone of the 1949 eruption of Mauna Loa lies on the caldera boundary, the eruptive fissure was not the caldera-boundary fissure, but one that extended across the center of the sunken caldera block, up over the caldera wall, and several kilometers down the flank of the mountain. But if the displaced magma does not rise around the sinking block, where does it go? Out into the rift zones? This brings us right back to Williams' Kilauean mechanism!

The failure of magma to rise along the caldera-boundary fractures itself calls for an explanation. The erupting basaltic magma has a specific gravity of about 2.7, and it appears likely that the magma even at the depth of the magma chamber has a density of only about 2.73 (Macdonald, 1963:1076). Compared with this, the gross density of the caldera-filling rocks is at least 2.8, and probably is between 2.9 and 3.0. If a mass of this density is underlain by a magma body of equal or greater horizontal dimensions and lower density, why does not the caldera block sink completely into the magma? The answer probably lies in the wedge form of the sinking block, bounded by fractures that dip inward instead of outward. Reynolds (1956) has pointed out that a downward convergence of the boundary fractures is implied by the up-bending of the edges of the lava beds filling many cauldron subsidences, including that of Glen Coe. The margins of the older, eroded Hawaiian calderas are seldom well enough exposed to reveal whether or not the edges of the beds are bent upward. However, Stearns (1940: Fig. 7) has described a basining of the lavas in the Koolau caldera, Oahu, and at least in one sector the beds filling the Kauai caldera are dragged slightly upward against the caldera boundary (Macdonald, Davis, and Cox, 1960:36). There is a definite implication that the boundary faults converge downward. Since sinking of a wedge-shaped block would tend to keep the boundary fractures tightly closed, this would also help to explain the failure of magma to rise to the surface along them and the lack of eruptive vents on the caldera boundary.

Why do the fractures converge downward, instead of diverging in the ring-dike manner deduced mathematically by Anderson (1936)? Perhaps the answer lies in the fact that the fractures were first established as a result of upthrust of magma beneath a relatively small portion of the mountain top, resulting in upward-divergent fractures of cone-sheet type, and that once established these fractures served as the surfaces on which the caldera block later sank. The tumescence frequently observed at Kilauea shows that magmatic pressure is great enough to push up the top of the mountain, and the piston-like rise of the caldera floor in the 1850's shows that at times the elevation takes place by displacement of a fault-bounded block rather than by quasi-plastic arching. Where upward pressure continues long enough cone sheets may form, like the numerous concentric inward-dipping dikes that surround the caldera of the Ofu-Olosega volcano in Samoa (McCoy, 1965); and concentric lines of spatter and cinder cones may form by surficial eruption on these fractures, as on some of the volcanoes of the Galapagos Islands (H. Williams, personal communication, 1964). In Hawaii, however, only a few dikes with the attitudes of cone sheets have been found, on Oahu and Kauai. Even fewer examples are known of eruption on concentric fractures, but one such line of cones lies just southwest of Kilauea caldera. For some reason, in Hawaii magmatic pressure has usually resulted in distension of the volcanic structure by upward bending of the summit followed by splitting open of the rift zones instead of lifting of the apex of the volcano on inward-dipping conical fractures.

A factor that must be explained before we can accept Williams' Kilauean mechanism is the very considerable discrepancy that exists between the volumes of some of the subsidences in the caldera during historic times and those of the simultaneously-erupted lava flows. The volumes of historic subsidences are listed in Table 1, the figures being taken from papers by Finch (1940, 1941) except the one for 1955, which is from Macdonald and Eaton (1964). The volumes for 1924 and 1955 include both marked collapses at Halemaumau and a general sinking of the whole mountaintop over a radius of 15 km or more, but this was undetectable without instrumental measurements in the earlier episodes of collapse. In these the figure given is only for the conspicuous sinking that took place in the caldera. Undoubtedly, however, a wider-spread general subsidence, like those in 1924 and 1955, also took place during each of the earlier episodes of collapse, and the volumes of those were accordingly greater than shown. The volumes of the lava flows are taken from Stearns and Macdonald (1946), again except for that of 1955. They include estimates of the volume of subaerial flows that entered the ocean; but the volumes, and even the existence, of any eruptions that may have taken place below sea level are wholly unknown.

A mere glance at Table 1 shows that there are large discrepancies between the volumes of several of the collapses and those of the accompanying lava flows. The smaller of the discrepancies, such as those for 1840 and 1955, can reasonably be attributed to intrusion of magma as dikes in the rift zones. The volume of extrusion in 1868 can only be guessed at, because we do not know the depth of the fill in Kilauea Iki crater. However, the eruption on the southwest rift zone had a volume of less than 200,000 m^3, and that in Kilauea Iki cannot be reasonably assumed to have been much more than 5,000,000 m^3 and may well have been a good deal less than that, so that we are left with a discrepancy of something more than 180,000,000 m^3. This also could be accounted for by the intrusion of an unusually large dike, averaging about 2 m thick and 2 km high above the top of the magma chamber, and extending 45 km across the top of the volcano. (Both rift zones opened during the eruption.) The volume of lava erupted above sea level in 1832 also is not accurately known, but it was very small. Furthermore, the only known vents were above the level of the caldera floor, so that eruption from them can hardly be considered a simple draining of magma from beneath the caldera block, allowing the latter to sink. On the other hand, the sinking of the block may have helped squeeze some magma to the surface. In 1924 there was no eruption of lava whatever above sea level. The discrepancies between the subsidences of 1823, 1832, and 1924 and the volume of known contemporaneous lava flows above sea level are, respectively, more than 525 million, approximately 580 million, and 200 million m^3. During the 1924 subsidence the east rift zone opened for a distance of more than 45 km, to and beyond the east cape of the island, and Jaggar (1934) believed that a submarine eruption occurred. It is certainly a distinct possibility, and the same could have happened during any of the other episodes of subsidence. An eruption in deep water would quite likely have escaped detection. The volume discrepancies can reasonably be attributed to rift-zone intrusion and/or submarine eruption.

Thus, the facts that must be taken into consideration in a theory explaining caldera formation appear to be: Caldera collapse takes place generally, if not always, following a period of tumescence of the volcano, accompanying or directly following an opening of one or both of the main rift zones, commonly accompanied by subaerial flank eruption and/or possible submarine eruption; and the sinking takes place on fractures that converge downward, which in turn means that sufficient outward movement of the circumferential mass must take place to make room for the increasing diameter of the sinking wedge at any given level. The distension of the summit region is very probably a part of, and is caused by the same mechanism as, the simultaneous distension of the rift-zone regions. Although eruptions are nearly always accompanied by a general sinking of the mountaintop, caldera collapse may not take place. Eruption may be confined to the caldera or the immediate summit region without any apparent opening of the rift zones, or opening of the rifts only close to the caldera.

The following possible interpretation of the above facts, together with the other facts as to the general structure of the volcano presented earlier, is suggested. Magma very rich in olivine crystals rises from the mantle into the volcano, adding to the bulk of the ultradense core; and part of the liquid portion of the magma rises on upward, leaving behind most of the load of solid crystals, to form a pool of fluid tholeiitic basalt in a high-level magma reservoir at the top of the ultra-dense core or, in some volcanoes, somewhat to one side of the top of the core, beneath the summit of the shield and extending outward beneath the near-summit portions of the rift zones. The volcano swells in response to the addition of magma. Local cupolas on the magma body may rise high enough to perforate the roof, allowing long-continued open-vent activity such as the lava lake that existed in Halemaumau crater most of the time through the 19th and early part of the 20th centuries, or the eruption in Mokuaweoweo during most of 1873 and 1874. Occasional withdrawals of magma from the cupolas may allow the collapse of pit craters in and near the caldera and along the rift zones. Eventually the top of the mountain splits open and some of the fluid tholeiitic magma rises to the surface, allowing the volcano to detumesce. The force that drives the magma to the surface is primarily the hydrostatic pressure on the magma body resulting from the weight of the overlying rocks, but as the magma gets very close to the surface there is added to this the expansive force of the gas that is separating from solution. Eruptions of this type are confined to the summit region.

As the mass of ultra-dense material in the core of the volcano grows, from time to time its weight becomes sufficient to cause a slight pushing apart of its confining walls in the lower part of the volcanic structure. This results in a splitting open of the volcano as a whole, including one or both of the rift zones and the summit region. Magma drains outward into the rift zones, and commonly flank eruption results. The volcano detumesces, and if distension of the summit region has been sufficient to allow sinking of the wedge-shaped caldera block true caldera collapse ensues. At other times, without any appreciable downfaulting of the caldera block, the detumescence may be simply a gentle over-all sinking detectable only by instrumental methods (as it commonly is in the case of summit eruptions); or it may be accompanied by marked collapse only at points where the underlying magma body approaches or reaches the surface, such as the collapse of Halemaumau crater during the subsidence of 1924 or the basining of the caldera floor in 1868 and 1894. Sinking of the caldera block depends on distension of the summit more than on draining away of the underlying magma, since the heavy rock of the caldera fill can sink indefinitely into the less dense magma. However, sinking of the caldera is generally accompanied by lateral movement of the underlying magma into the rift zones because the same lateral displacement that stretches the summit region enough to allow sinking of the caldera block also opens the rift zones, and room for the sinking is largely provided by drainage of magma into the rift zones. Some magma is squeezed out in the summit region by sinking of the overlying rocks, but the denseness of the caldera-filling rocks and the wedge shape of the sinking block keeps the underlying conical subsidence fractures tightly closed and largely prevents the rise of magma through them. Discrepancies between the volume of summit sinking, including caldera collapse, and the volume of lava extruded in subaerial eruptions (both flank and summit) are accounted for partly by intrusion into the rift zones, probably partly by submarine eruption, at times partly by squeezing of magma upward into fissures in overlying rocks, and partly by space provided by the slight sinking of the top of the ultra-dense core as a result of spreading of its lower portion.

The eruption is brought to an end by drainage of the easily-eruptible magma down to the level of the opening of the fissures, but the eruption may be prolonged by rise of additional magma from deep levels, as appears probably to have been the case during the 1959 eruption in Kilauea Iki (Richter and Eaton, 1960). Afterward the volcanic structure is sealed by partial or complete congealing of magma in the fissures, and the whole cycle repeats itself as more ultra-dense magma rises from the mantle and more tholeiitic magma accumulates in the shallow magma reservoir.

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